# LCLS-II Gun/Buncher LLRF for the Early Injector Commissioning

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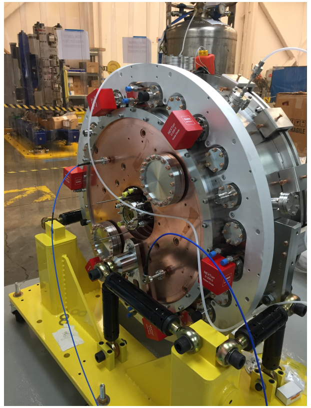
U.S. DEPARTMENT OF ENERGY | Office of Science

ACCELERATOR TECHNOLOGY & APPLIED PHYSICS DIVISION ATAP

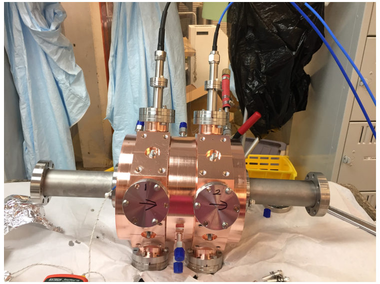
# Outline

- Introduction
- System design
- Bench test and System checkout
- System commissioning
- Summary

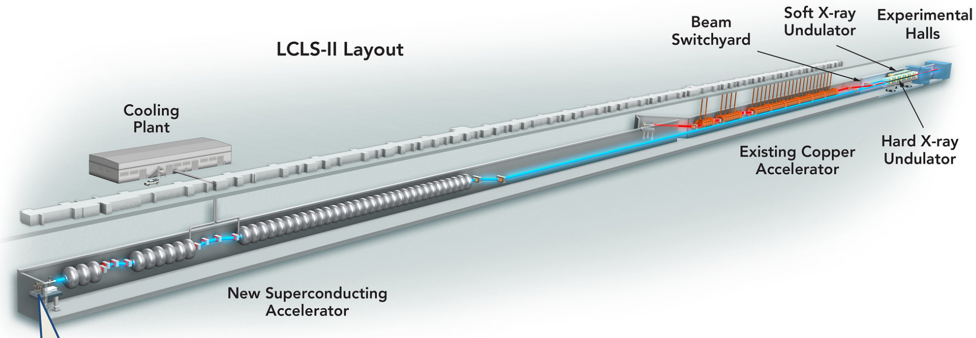
# LCLS-II Gun and Buncher



| | |
|---|---|
| RF frequency | 186 MHz (1.3 GHz /7) |
| Operation mode | CW |
| Gap voltage | 750 kV |
| Field at the cathode | 19.47 MV/m |
| $Q_0$ | ~ 26000 |
| Shunt impedance | 6.5 MW |
| RF Power @ $Q_0$ and 750 keV | ~ 100 kW |
| Peak surface field | 24.1 MV/m |
| Peak wall power density | 25.0 W/cm$^2$ |
| Accelerating gap | 4 cm |
| Diameter/Length | 69.4/35.0 cm |
| Operating pressure | ~ $10^{-10}$-$10^{-9}$ Torr |



| Parameter | Value and Unit |
|---|---|
| Technology | Room-temperature 2-cell cavity |
| Operation mode | Continuous wave (CW) |
| Frequency ($\pi$ mode) | 1.3 GHz |
| Minimum separation mode | 0.85 MHz |
| Nominal cavity voltage | 240 kV |
| Nominal shunt impedance | 7.8 MΩ |
| Nominal unloaded Q ($\pi$ mode) | 23,500 |
| Nominal RF power | 7.8 kW |
| RF source maximum power | 10 kW |
| Number of RF couplers | 4 (2 per cell) |
| Coupler type | magnetic |
| Maximum flange-to-flange length | 21.9 cm |
| Minimum beam pipe radius | 2.5 cm |
| Maximum operational vacuum pressure | < 1 nTorr |




NC injector for the SRF linac

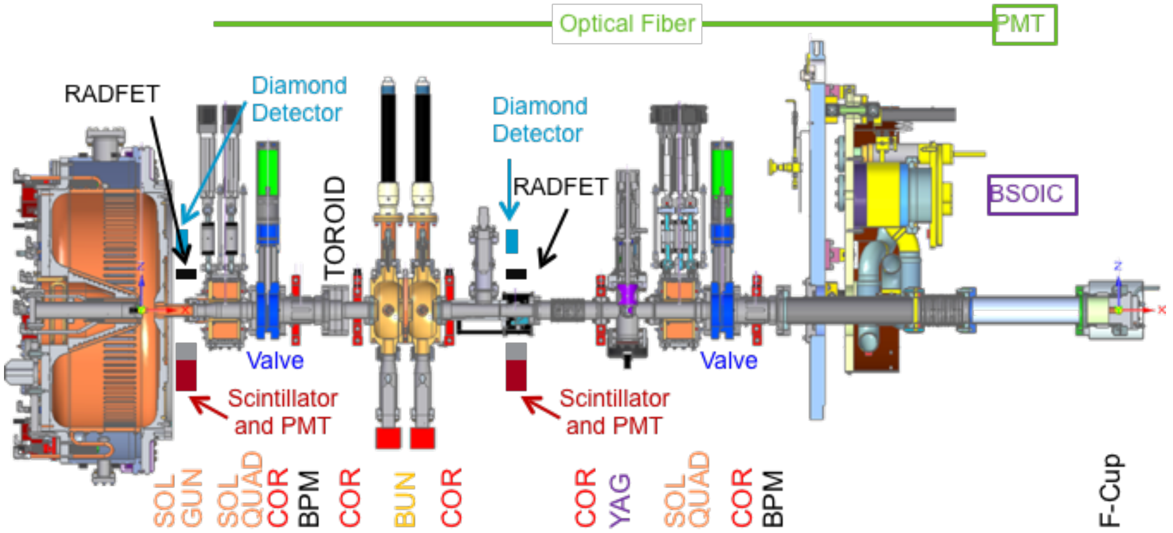
Low level RF requirements for the injector

| | RF itter | Arrival time change (fs) |
|---|---|---|
| Laser timing | 80 fs | 48 |
| Gun phase | 0.04 ° | 32 |
| Gun amplitude | 0.01% | 45 |
| Buncher phase | 0.015 ° | 43 |
| Buncher amplitude | 0.03% | 12 |
| Cav1 phase | 0.05 ° | 20 |
| Cav1 amplitude | 0.03% | 17 |
| Total arrival time changes at 95 MeV (at 4 GeV after 100 times bunch compression) | - | 90 (< 1) |

# Early Injector Commissioning (EIC)

The project decide to commission the injector way ahead of the rest of the machine to gain experience with the system and reduce the overall project risk

- Temporary shielding
- Essential diagnostics
  - BPM
  - Toroid
  - F-Cup
  - YAG
  - BLM
- Control system
  - LLRF
  - Laser
  - Software
- Operation
  - GUIs
  - Procedures



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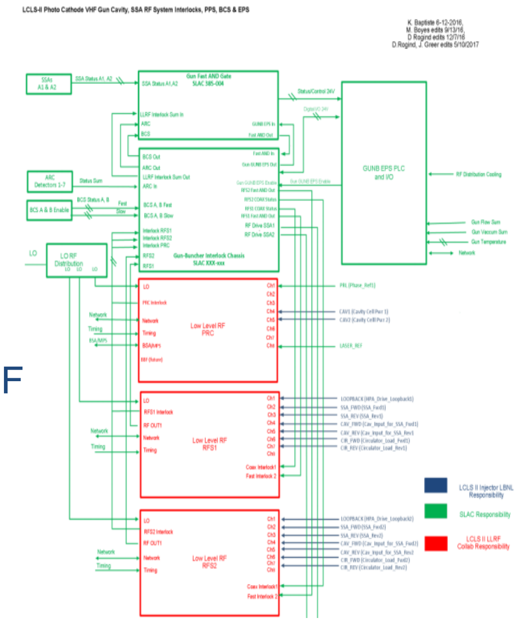
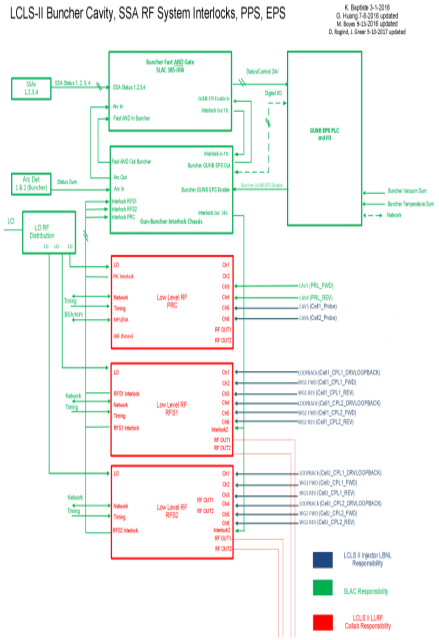
# Gun/Buncher LLRF system and interface

- Follow LCLS-II SRF LLRF architecture
  - 1 Precision Receiver Chassis (PRC) + 2 RF Stations (RFS)
  - Fiber link among chassis
  - Lots of monitor channels
- Only one amplitude/phase loop per system
  - Loop runs on PRC
- Resonance control actuators are not part of LLRF responsibility
  - Motor/piezo controller for gun
  - Water temperature system for buncher
- Not part of safety system
  - Receive Enable signal from safety system



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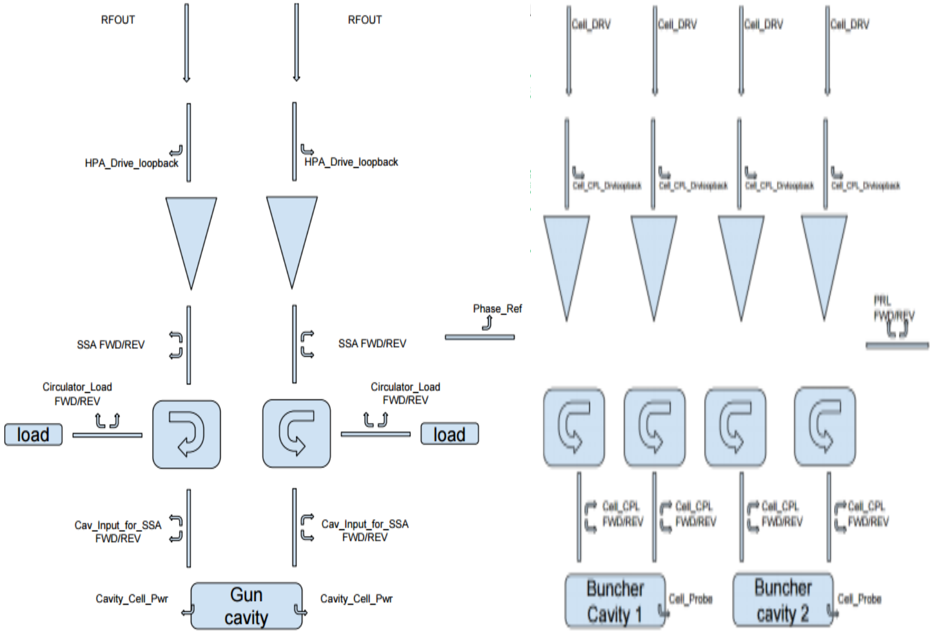
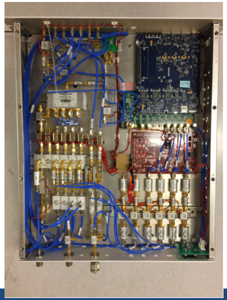
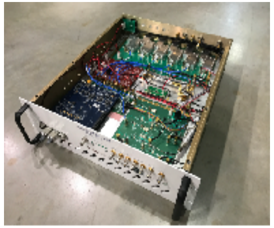


# Gun/Buncher LLRF hardware design

- Gun LLRF chassis
  - Quantity: 1 set + spare
  - Connectorized APEX style RF front end
  - Each chassis have 8 ADCs 2 DACs channels
  - BMB7 FPGA carrier card
    - SRF move on to QF2 later
  - Same digitizer card
- Buncher LLRF chassis
  - Same production SRF LLRF chassis
  - Except FPGA carrier board

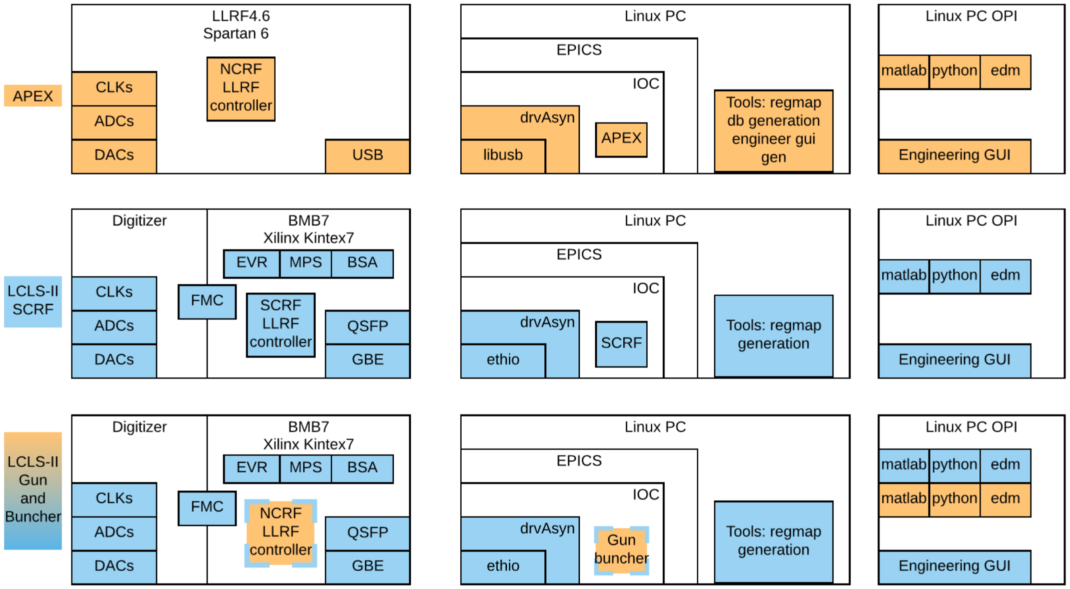





# Gun/Buncher LLRF firmware and software design

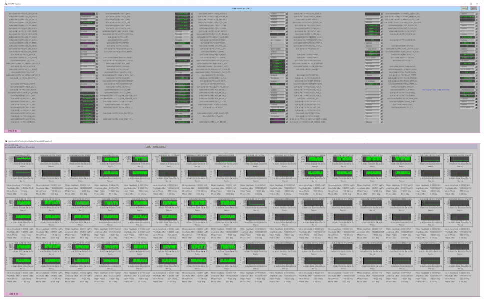
## Merge APEX code with LCLS-II SCRF LLRF code

- Firmware
  - NCRF LLRF from APEX
  - Board support layer from SCRF
  - EVR/MPS/BSA integration depends on the SCRF LLRF
- Software
  - Based on the SCRF LLRF EPICS IOC
  - APEX like process
- New features
  - Separated DAC drive for multiple amplifiers with adjustable phase

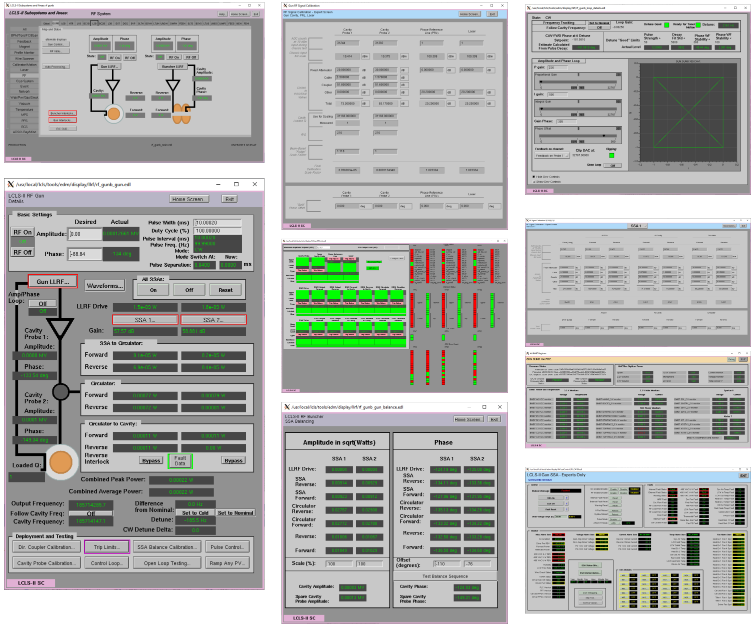


# Gun/Buncher RF/LLRF OPI design

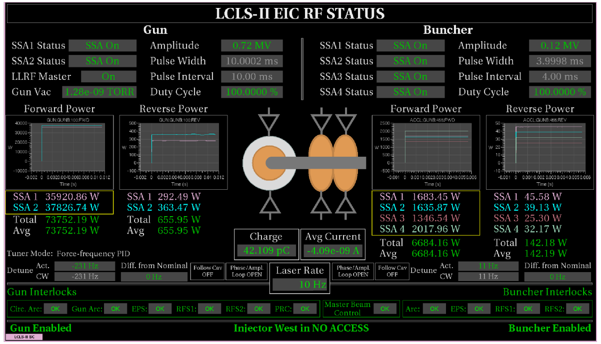
Hardware registers and waveforms

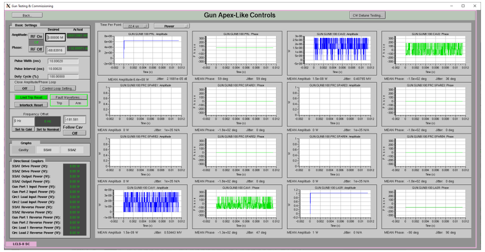


SLAC style engineering/operating GUIs



Top level status report



APEX like operating GUI

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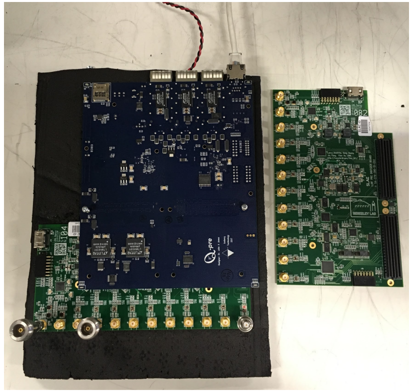
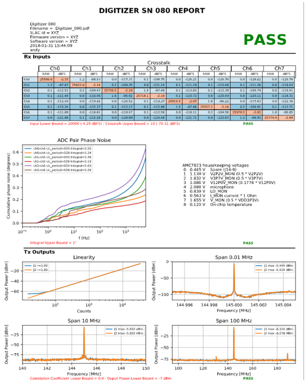
# Hardware bench test

- Boards test
  - Digitizer ADC channel isolation, phase noise
  - DAC channel linearity, output spur
- Chassis test
  - Channel  to channel  isolation
  - Receiver linearity and phase noise
  - RF port S11
  - Drive power level






## RFS/PRC Test procedure

### Scope

This test procedure is used to test either LCLS2 Precision Receiver Chassis (PRC) or RF Station chassis (RFS). Some portions of this test are only applicable to the RFS. When testing a PRC, note the un-needed fields with a 'NA'. When this document is completed after a test, it should be uploaded to the chassis record in the SLAC Depot database. Please note the chassis type and date below. The completion date should be entered after the test is complete.

Data in this procedure should be added digitally. To start the test process, obtain a blank copy of the procedure and save the file according to the chassis type and the serial number, i.e.:

Filename = 'RFS_18051417'

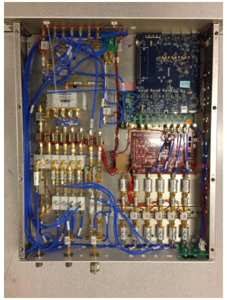
| Chassis type (RFS/PRC) | Chassis serial number | Test completion date |
|---|---|---|
| GUNPRC | - | Jul 20, 2017 |

### Serial Numbers

A SLAC ID number should be applied to each chassis and each of the following boards in the chassis. The Serial number of the board should also be recorded. The chassis serial number is the same as the SLAC ID. The up and down converters also retain a digital serial number. The bitfile for the BMB7 should also be recorded. The digital serial numbers and bitfile can be found later in this procedure.

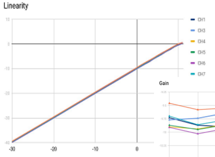
Table 1: Serial numbers

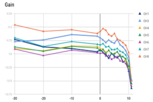
| Component | Part Number | Serial Number | Digital Serial Number, or bitfile name | SLAC ID number |
|---|---|---|---|---|
| Chassis | | GUNPRC | NA | |
| BMB7 | BMB7 | RKT-16162554 | | |
| Digitizer board | R1.0 | 007 | NA | |
| Down converter | RevB1 | | | |
| Up converter | | | | |

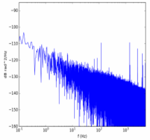


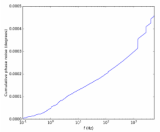
GUNRFS02 Digitizer input signals and isolation

| dB | ch1 | ch2 | ch3 | ch4 | ch5 | ch6 | ch7 | ch8 |
|---|---|---|---|---|---|---|---|---|
| ch1 | 0.0 | -81.9 | -116.5 | -111.3 | -98.4 | -103.0 | -112.3 | -111.6 |
| ch2 | -81.4 | 0.0 | -99.9 | -115.0 | -114.6 | -115.3 | -113.1 | -115.9 |
| ch3 | -117.5 | -105.9 | 0.0 | -82.0 | -114.0 | -117.3 | -108.3 | -104.9 |
| ch4 | -112.8 | -115.3 | -81.5 | 0.0 | -115.6 | -113.4 | -110.9 | -105.5 |
| ch5 | -98.0 | -106.9 | -114.1 | -113.1 | 0.0 | -83.5 | -108.8 | -114.1 |
| ch6 | -100.3 | -108.6 | -115.0 | -113.2 | -82.2 | 0.0 | -104.1 | -112.4 |
| | | 2.7 | -104.7 | -106.0 | -108.6 | -103.0 | 0.0 | -85.4 |
| | | 7.0 | -101.8 | -104.7 | -117.3 | -108.5 | -85.6 | 0.0 |



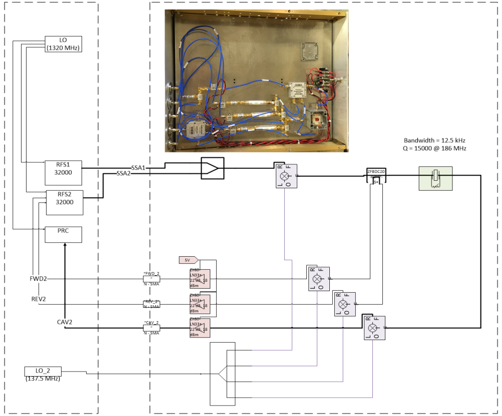


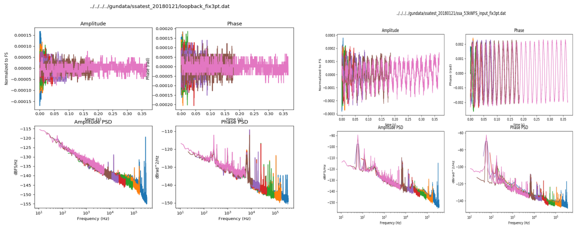
| DAC count | dBFS (dB) | DAC1 out (dBm) | DAC2 out(dBm) |
|---|---|---|---|
| 2000.0 | -24.3 | -13.7 | -14.1 |
| 4000.0 | -18.3 | -7.6 | -8.1 |
| 8000.0 | -12.2 | -1.8 | -2.1 |
| 16000.0 | -6.2 | 4.1 | 3.7 |
| 32000.0 | -0.2 | 9.1 | 8.8 |

# Rack test

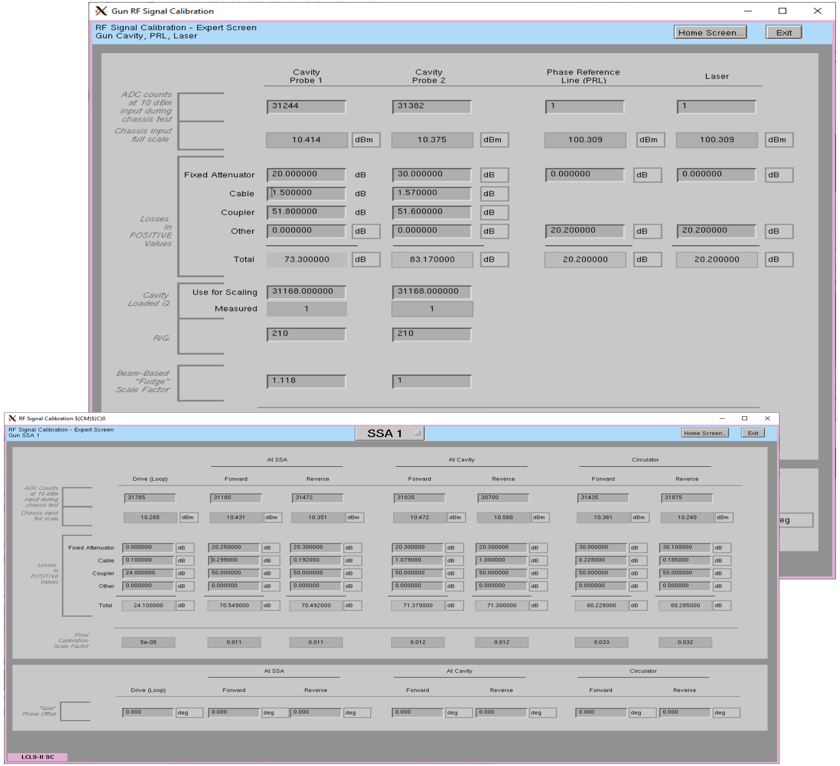
Testing rack assembled in B15 @SLAC

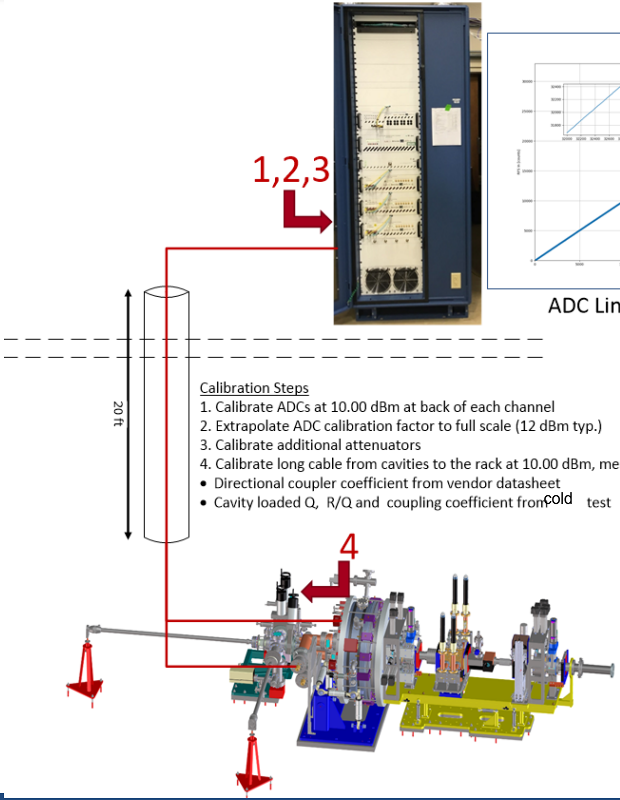
- Crystal based cavity emulator 12.5kHZ BW, ~Q185=16000
- Test with SSA
- Develop and debug EPICS IOC and GUI

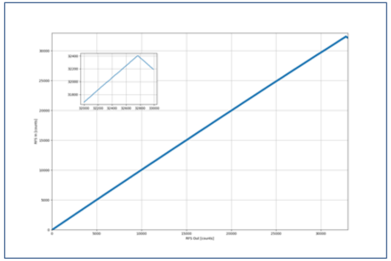



# Cable/coupler/cavity calibration coefficient



ADC Linearity to saturation

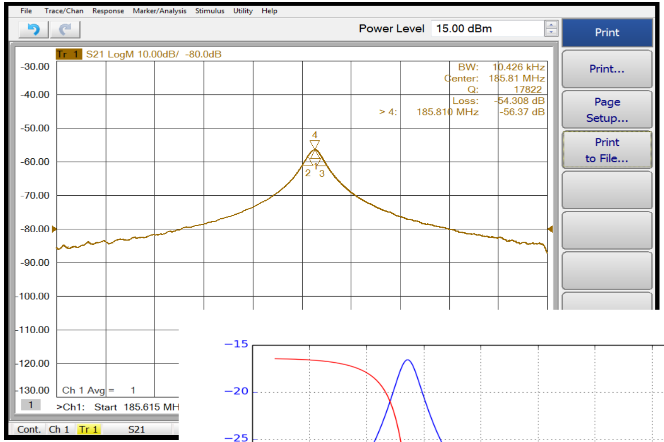
<u>Calibration Steps</u>

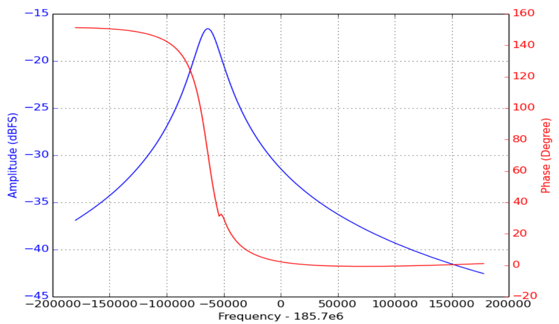
1. Calibrate ADCs at 10.00 dBm at back of each channel
2. Extrapolate ADC calibration factor to full scale (12 dBm typ.)
3. Calibrate additional attenuators
4. Calibrate long cable from cavities to the rack at 10.00 dBm, measured by live LLRF waveform aquisition

- Directional coupler coefficient from vendor datasheet
- Cavity loaded Q, R/Q and coupling coefficient from cold test

# LLRF cavity test with tiny power

- VNA scan withSSA bypassed
  - 1 W total RF power gun
  - 2 W total for buncher
- Software development
- Enabled practice on balancing and detune calculation
- When EIC was ready for high power, LLRF system was already proven



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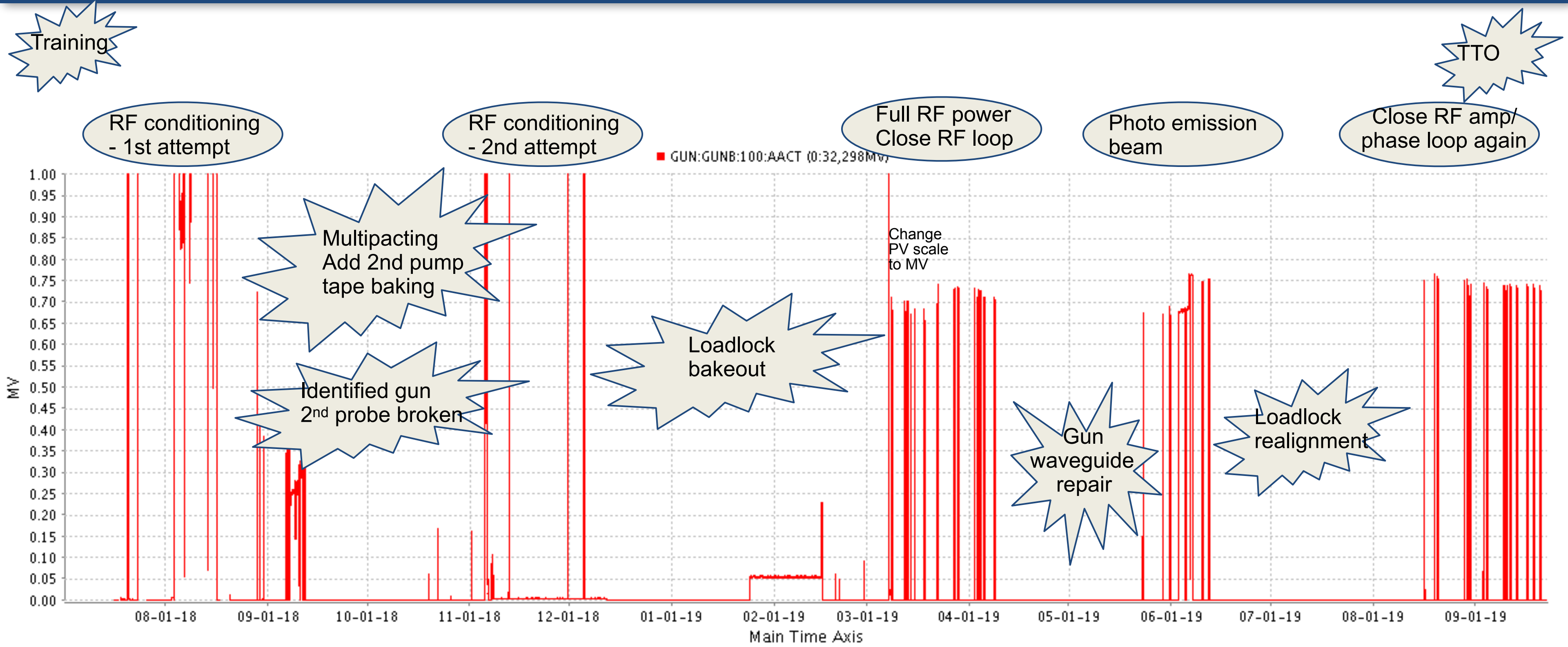
# Gun/Buncher LLRF and EIC milestones

- 2016.10.03 Peer review
- 2016.12.08 Preliminary design review
- 2017.7.27 Final design review, gun chassis bench tested
- 2017.12 - 2018. 6 Rack test / SSA test B15 @ SLAC
- 2018.4.24 EIC readiness review
- 2018.7 Chassis installation, 1W test
- 2018.4-2018.8 tape baking
- 2018.8 RF on, observe dark current
- 2018.9 Full power on gun and buncher
- 2018.9-2019.4 bake out
- 2019.4 Full power, CW, close loop on gun and buncher
- 2019.5.29 First photoemission beam
- 2019.6 Continuous operation, measure beam power, repetition rate
- 2019.8 Measure beam charge
- 2019.9 Injector source TTO

# Early Injector Commissioning



# Detune and frequency tracking

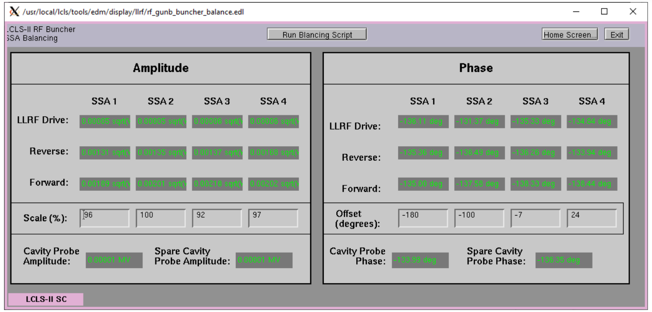
- Cavity frequency change when warm up
  - Gun start at ~300kHz away
  - Buncher start at ~500kHz away
  - Thermal effect, so slow variation
  - EPICS based resonance control
- Detune calculation
  - Pulse mode
    - Curve fitting on falling edge decay waveform
    - Directly frequency difference
  - CW mode
    - Analysis forward and probe phase
    - Phase difference from cable length difference

- Tuner track the gun frequency
  - Tuner range / Speed / Granularity
- Water temperature track buncher frequency
- LLRF track the frequency
  - Adjust drive frequency in software
  - "Self excited mode" in firmware
- Original scope did not include frequency tracking, APEX use it routinely.
- LLRF frequency tracking has been very valuable for gun tuner commissioning

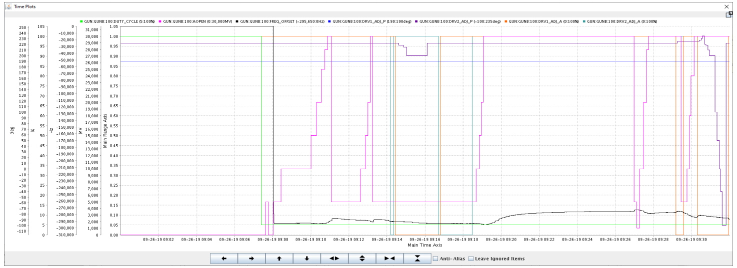
# Balancing multiple drives

Adjust relative amplitude and phase among different drives to minimize reflection

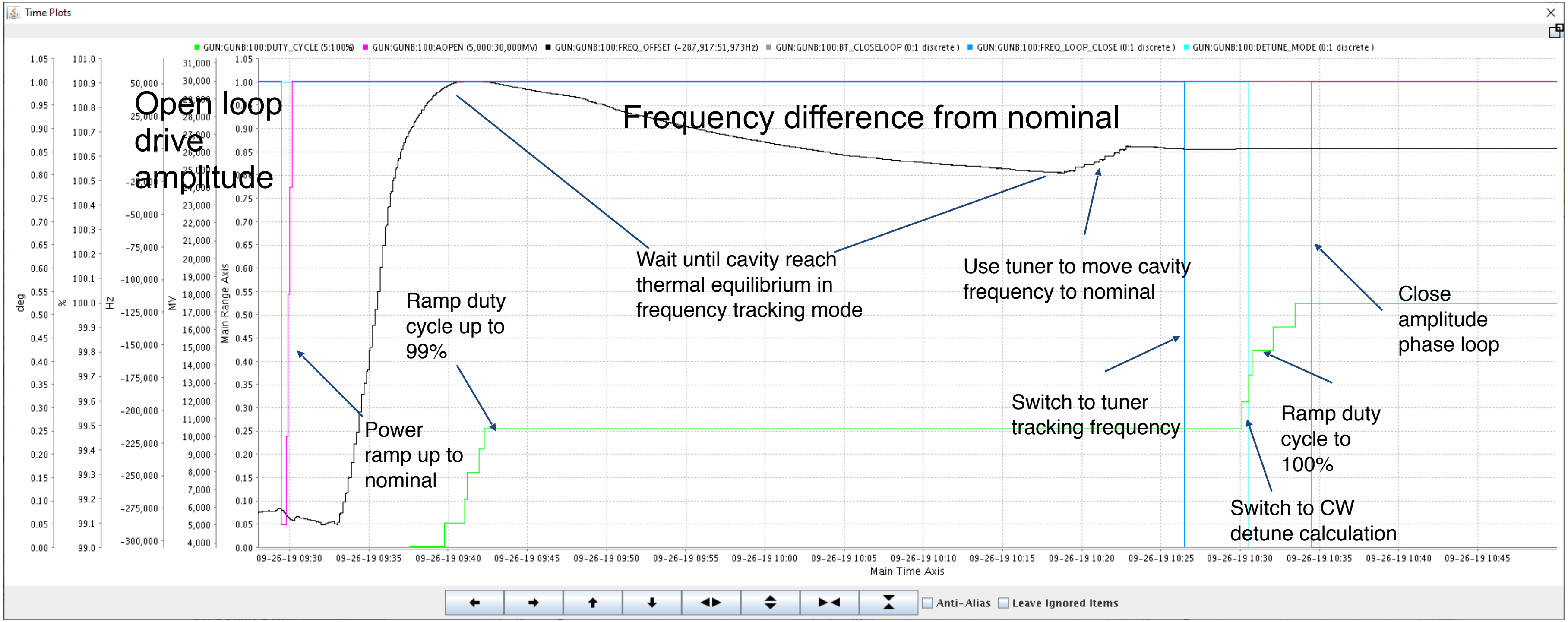
- Corse  adjustment at low power low duty cycle
    - Drive only with single SSA
    - Measured one probe amplitude and phase
    - Calculate coefficient by pseudo inverse
- Adjust at high power as need to achieve lowest reverse power
- Fine Adjust as needed along the way







# Turn on procedure on a good day



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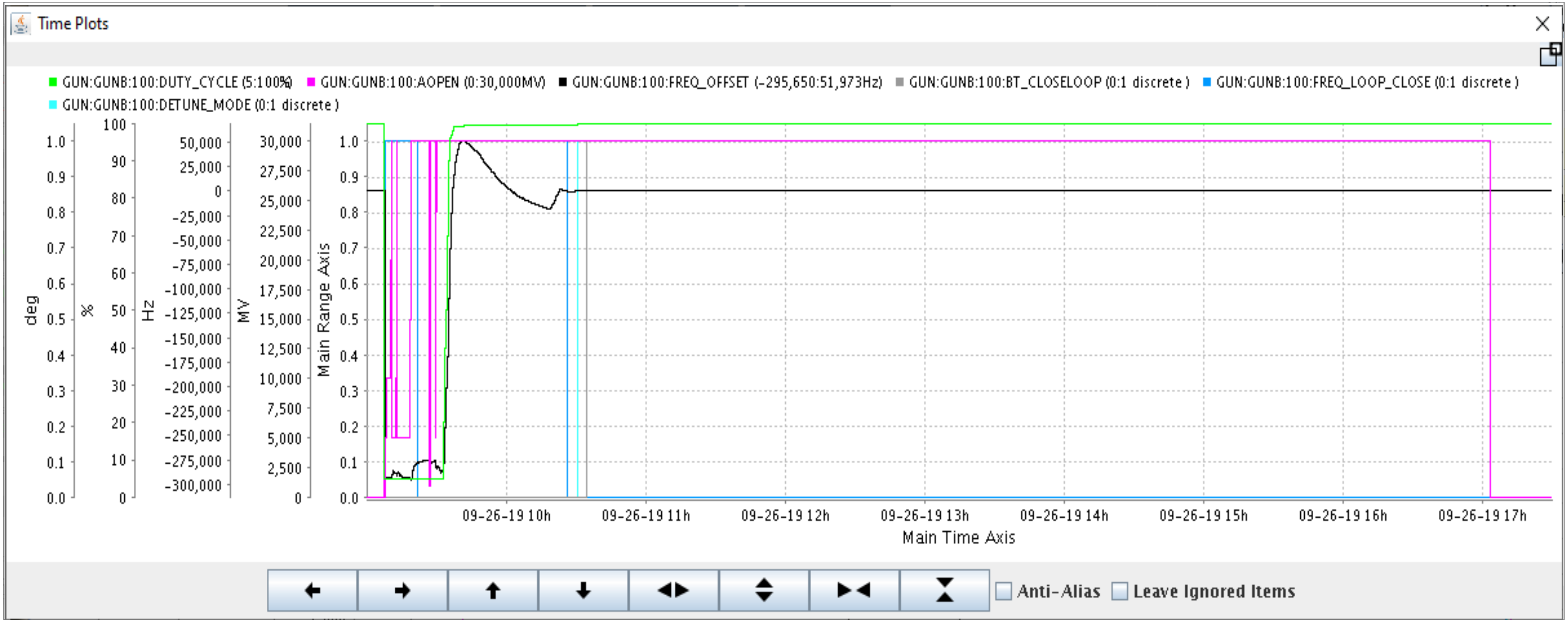
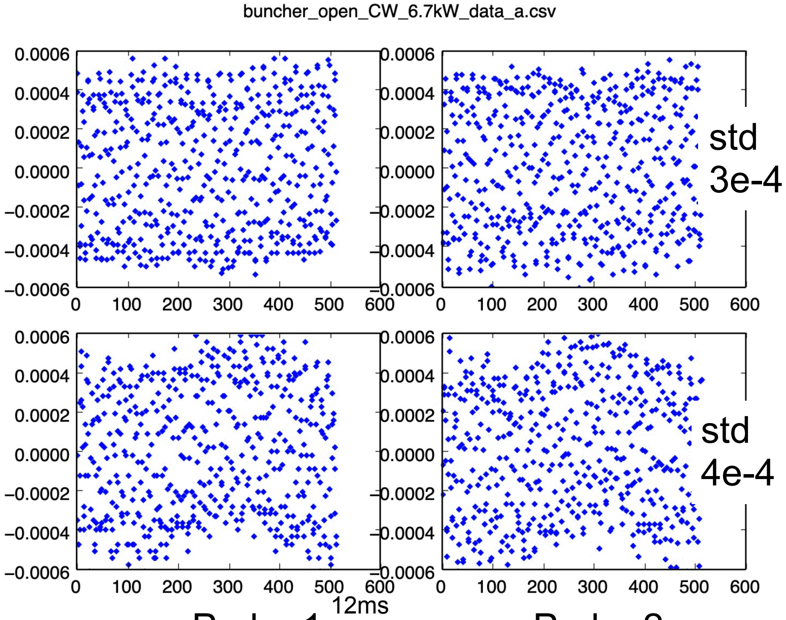
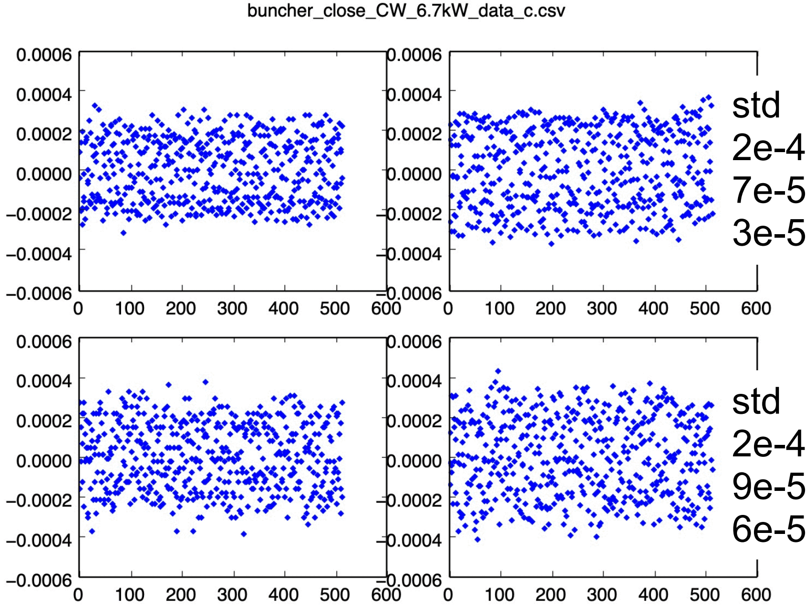


# Buncher cavity field stability short term (12ms)

Open loop

Close loop with different gains




Amplitude

phase

dt=22.4us

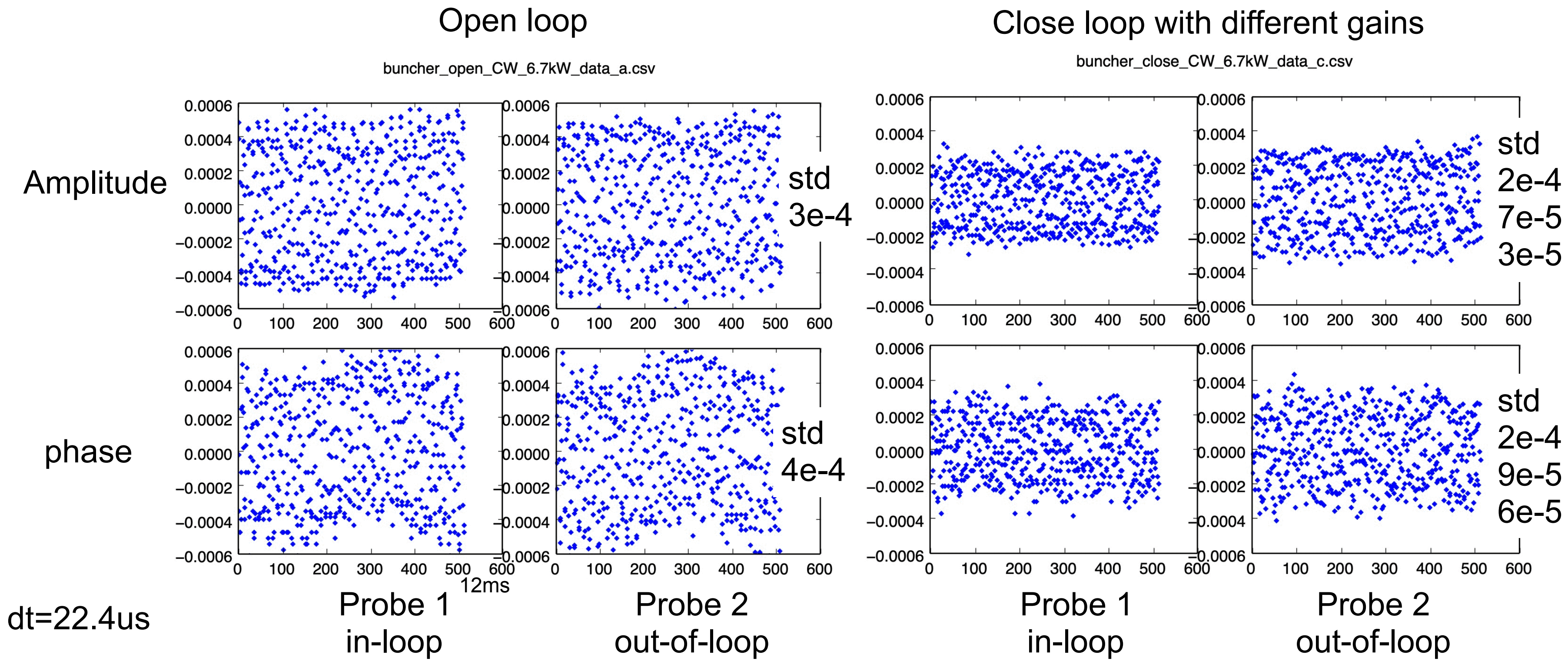
Probe 1
in-loop

Probe 2
out-of-loop

Probe 1
in-loop

Probe 2
out-of-loop

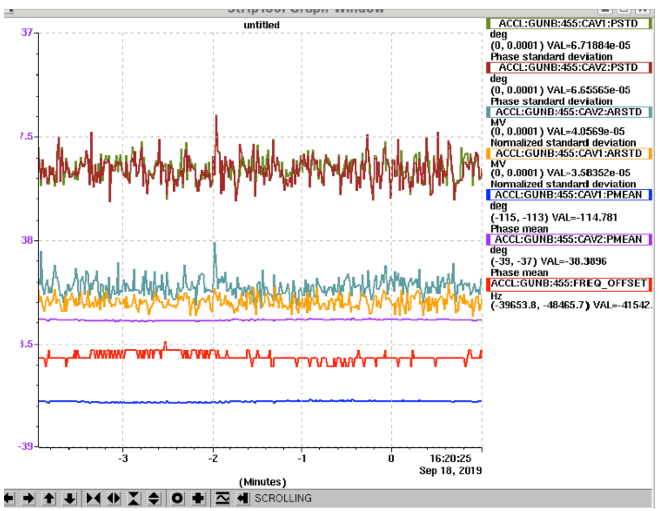
# Buncher cavity field stability short term (12ms)

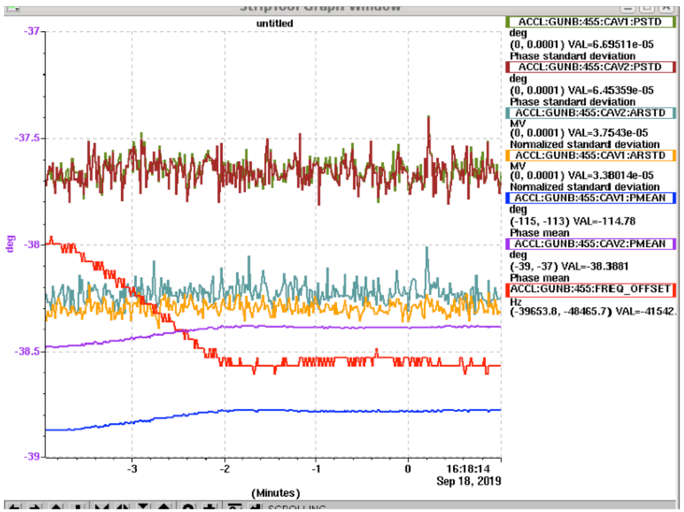



dt=22.4us

# Buncher cavity field stability mid term (5 min)

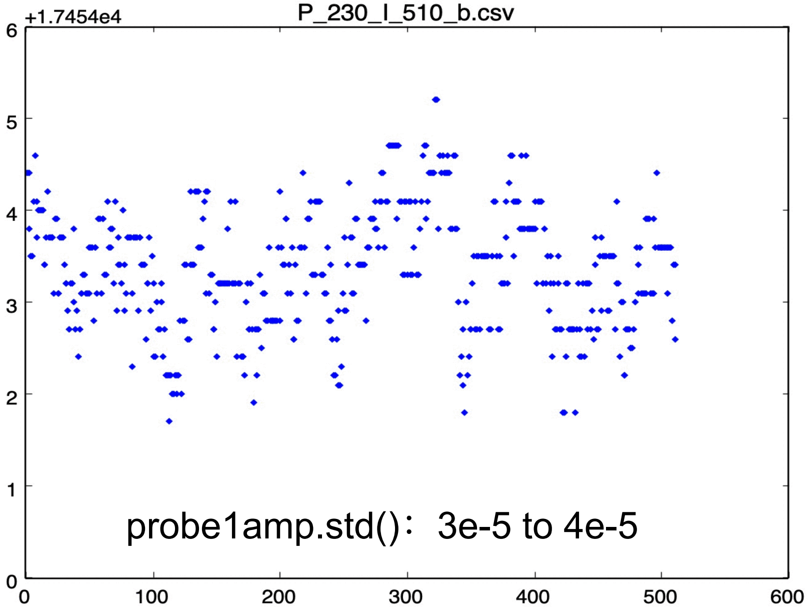
Probe1phase.mean()
Probe2phase.mean()
probe1phase.std()
probe2phase.std()
probe1amp.std()
probe2amp.std()
frequency offset

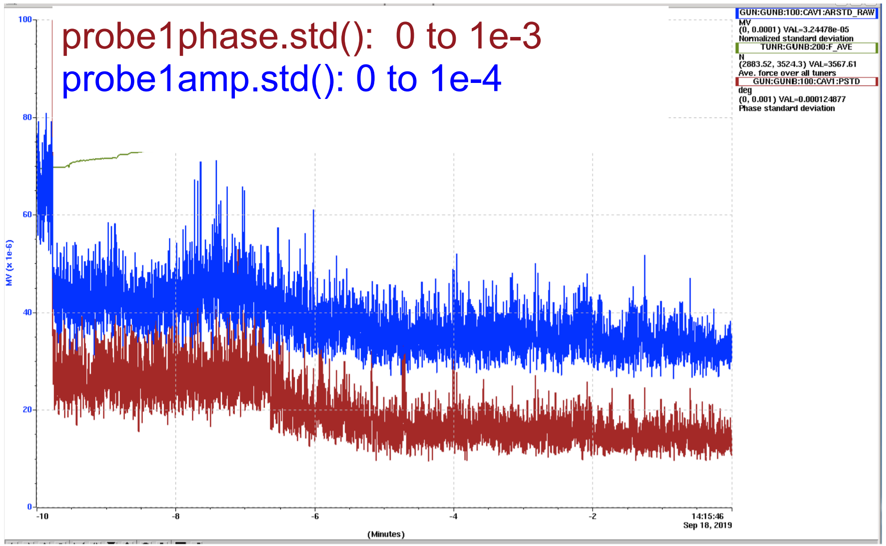


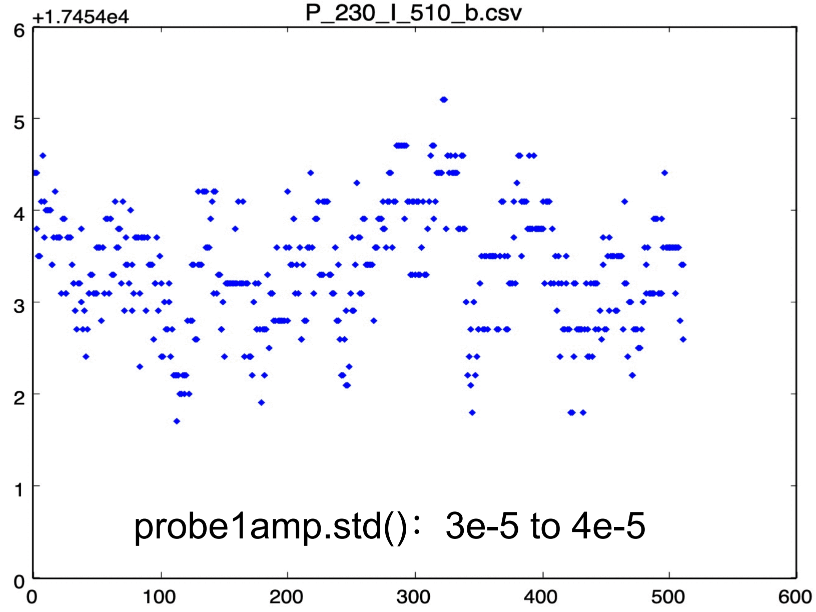

Scale for standard deviation is 0 to1e-4
Cavity frequency change drive the phase away

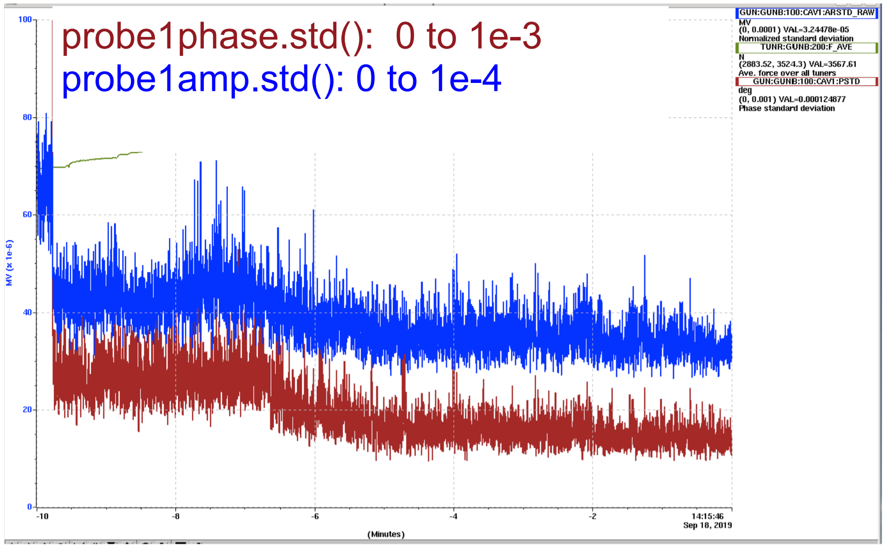
# Gun cavity field amplitude short term stability (12ms)



# Gun cavity field amplitude short term stability (12ms)



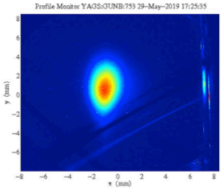



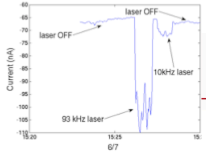
# Not so good days

# Physicists and operators run EIC for beam test

## First Photoelectrons

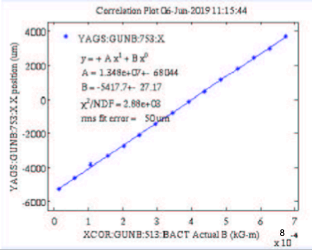
- Background subtracted image
  - Uncoated Mo cathode (low QE)
  - 0.5 pC/bunch (measured on pico-ammeter with 60% duty cycle)
  - 10 kHz laser rep rate
  - TTO requires 20 pC/bunch
- Pico-ammeter signal with laser on/off at 10 and 93 kHz
  - Dark current has risen from 0.00005 to 0.0005 pC/bunch
  - Specification is 0.002 pC/bunch
  - Expect high dark current due to rough dummy cathode
  - Will measure again with $Cs_2Te$ cathode installed



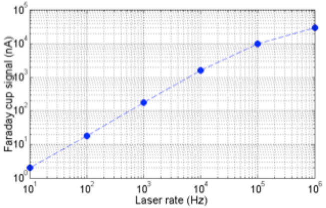

## Beam Energy 760 keV

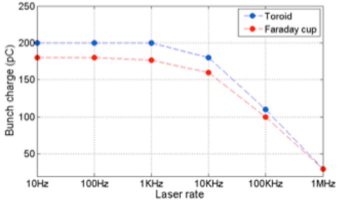
- 84 kW rf power input
  - Expected energy is 680 keV
  - ≈ 10% uncertainty
- Beam based energy measurement measures 760 keV
  - Resolution is about 10 keV




## Charge Measurements

- Laser pulse energy decreases as repetition rate increases
  - Thermal lensing problem in the harmonic crystal
  - Will implement telescope to change beam size at high rep rates
- Approximately 5 nA of dark current at the Faraday cup
  - Dark current specification is <400 nA
  - Dark current decreasing over time with RF on
- QE ≈ 0.3%
  - Consistent with 1.5% QE measured in deposition laboratory in May



# Transitioned to Operations

| System | Parameter | TTO Goal | Achieved |
|---|---|---|---|
| Injector Source | UV Laser Pulse Energy @ cathode | 0.03 μJ | 0.3 μJ |
| | Beam Energy | 500 keV | 760 keV |
| | Charge | 20 pC | >200 pC |
| | Repetition Rate | 93 kHz | >900 kHz |

# Summary and looking forward

- EIC
    - EIC complete
    - Operations will continue to optimize, improve performance through October
    - Install improved hardware in November (RF probe, buncher coupler, gun tuner motors, buncher chiller etc)
    - Rebake gun and verify operation in December/January
- LLRF
    - Gun/Buncher LLRF system successfully run the cavities to meet the EIC requirement
    - Upgrade FPGA carrier to QF2 and IOC to FEED based
    - Implement additional feature requested during EIC
    - Real full system stability analysis

Thanks to the LCLS-II LLRF collaboration team

Thanks to the LCLS-II EIC team

# Thank you for your attention

Brunch mode GUI from Alex Saad